View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Elsevier - Publisher Connector

ELSEVIER
CrossMark
Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 147 (2016) 677 – 682
Procedia Engineering
www.elsevier.com/locate/procedia

11th conference of the International Sports Engineering Association, ISEA 2016

The effect of ball spin rate on distance achieved in a long soccer throw-in

Nicholas P. Linthorne[a]*, Jamie M. Thomas[b]

[a]*Department of Life Sciences, Brunel University London, Uxbridge, London, UB8 3PH, United Kingdom*
[b]*British Rowing, Hammersmith, London, W6 9DJ, United Kingdom*

Abstract

In this study a skilled soccer player performed throws for maximum distance while manipulating the backspin on the ball. A video analysis was used to obtain measures of the ball projection variables. We found that putting greater backspin on the ball did not reduce the player's ability to produce a high projection velocity. Throw distance increased at a rate of about 0.6 m per 1 rev/s increase in backspin, and the experimental data was consistent with the predictions of a mathematical model. We recommend players apply the highest possible backspin when performing a long throw-in.

© 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of ISEA 2016
Keywords: aerodynamics; backspin; biomechanics; football; lift coefficient; soccer; spin; throw-in

1. Introduction

The long throw-in can be a potent form of attacking play, particularly when used near to the goal mouth. The farther a player can throw the ball, the larger the area in which his/her team mates may receive the ball and the greater the scoring opportunities. Although the distance achieved in a throw-in is mostly determined by the player's ability to generate a high projection velocity, a player may also apply backspin to the ball to increase the throw distance. To the best of our knowledge there are no published experimental studies of the effect of ball spin on the distance achieved in a long soccer throw-in. However, Linthorne and Everett [1] reported results from a mathematical model of the throw-in. They found that the optimum projection angle for achieving maximum distance is about 30º and that throw distance is maximized when using a backspin rate of just over 4 rev/s.

Linthorne and Everett's study is an excellent example of the need to include the interactions between the equipment, the athlete, and the movement when analyzing a sport [2]. As would be expected, their model incorporated the influence of spin rate on the lift and drag coefficients of the ball. In addition, the model incorporated the biomechanics of the throwing action by including equations for the interdependence of the player's projection velocity, projection angle, and projection height. The decrease in projection velocity that a player can produce as projection angle increases has a strong influence on the optimum projection angle (reducing the optimum angle to well below 45º), and hence has a strong influence on the throw distance.

Even so, Linthorne and Everett's model might not have incorporated all the relevant biomechanics of the throwing action. Their model assumed that the player's projection variables are independent of the ball spin rate. Here, we recognize that attempting to put a high backspin on the ball might substantially reduce the projection velocity that a player is able to achieve. The purpose of the present study was to investigate in more detail the effect of backspin on the distance achieved in a long soccer throw-in. The main aims of the study were: (1) to obtain experimental data for the effect that applying spin to the ball has on the player's ability to produce projection velocity; (2) to obtain experimental data for the effect of ball spin on throw distance; (3) to identify the player's optimum ball spin rate that maximizes the throw distance; and (4) to compare the experimentally obtained relationship between ball spin rate and throw distance to the predictions of a mathematical model of the throw-in. In this study a skilled player threw a soccer ball for maximum distance while applying a wide range of backspins to the ball. The throws were

* Corresponding author. Tel.: +44-01895-266479; fax: +44-01895-269769.
E-mail address: nick.linthorne@brunel.ac.uk

1877-7058 © 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of ISEA 2016
doi:10.1016/j.proeng.2016.06.271

recorded on video and a 2-D biomechanical analysis was conducted to determine the player's projection variables. We expected that the act of applying backspin to the ball would reduce the player's projection velocity, and that this would have a substantial effect on the distance achieved and the optimum projection angle. The predictions of the mathematical model were expected to agree with the experimental data.

2. Methods

One skilled male soccer player volunteered to participate in the study. The study adhered to the tenets of the Declaration of Helsinki and was conducted in accordance with procedures approved by our institutional ethics committee. The participant was informed of the procedures and inherent risks prior to his involvement, and written consent to participate was obtained. The throws were performed in still air conditions in an indoor sports facility using a FIFA-approved, 32-panel, size 5 match ball (Nike T90 Strike) inflated to the regulation pressure. The participant wore his own sports clothes and shoes, and used a constant run-up length of two steps. The participant performed maximum-effort throws while attempting to achieve maximum throw distance (Figure 1). He performed five throws using his preferred technique, and 45 throws using a wide range of backspin, from "almost none" through to "the maximum possible". The order of ball spin was randomized and an unlimited rest interval was given between throws to minimize the effects of fatigue on performance. The throw distances were measured to the nearest 0.1 m using a fiberglass tape measure.

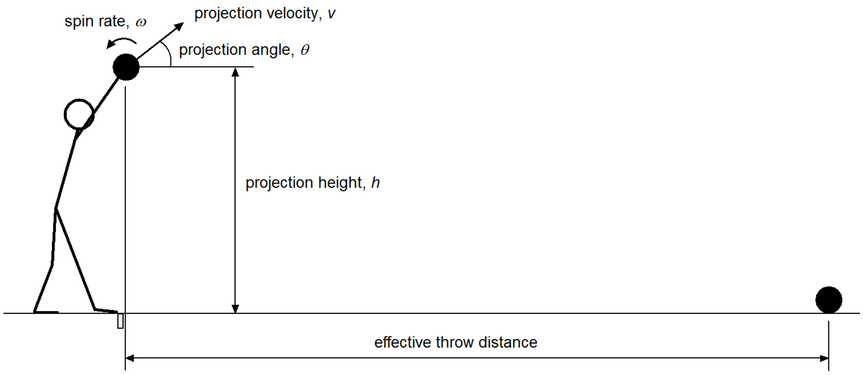


Fig. 1. Schematic diagram of a long soccer throw-in showing the projection variables that determine the effective throw distance.

2.1. Video analysis

A 2-D video analysis was conducted to quantify the ball projection variables. A JVC GR-DVL 9600 video camera (Victor Company of Japan, Yokahama, Japan) operating at 50 Hz was used to record the movement of the player and ball during the throws. The video camera was placed at right angles to the throw direction and about 15 m away from the plane of the throw. The field of view was zoomed to allow the participant and ball to be in the field of view throughout throw and for at least 12 frames after release. The movement space of the video camera was calibrated with three vertical poles that were placed along the plane of the flight of the ball.

An Ariel Performance Analysis System (Aerial Dynamics, Trabuco Canyon, CA, USA) was used to manually digitize the motion of the center of the ball and the participant in the video images. The center of the ball and eighteen body landmarks that defined a 17-segment model of the participant were digitized in each image. The two-dimensional coordinates of the ball and the body landmarks were calculated from the digitized data using the two-dimensional direct linear transform (2D-DLT) algorithm. Coordinate data were smoothed using a second-order Butterworth digital filter with a cut-off frequency of 8 Hz, and the velocities of the ball and the body landmarks were calculated by numerical differentiation of the coordinate data.

2.2. Data analysis

The instant of release was defined as the first frame in which the ball broke contact with the participant's hands. The projection height was the vertical distance of the center of the ball relative to the ground at the instant of release, and the projection distance was the horizontal distance of the center of the ball relative to the throwing line at the instant of release. The effective throw distance was calculated by adding the release distance to the measured throw distance.

The projection velocity of the ball was calculated using unfiltered ball displacement data from the first six images immediately after the instant of release [3]. The horizontal component of the ball velocity was calculated as the first derivative of a linear regression line fitted to the unfiltered ball displacement data, and the vertical component of the ball velocity was calculated as the first derivative of a quadratic regression line (with the second derivative set equal to –9.81 m/s^2) fitted to the unfiltered ball displacement data [4]. The projection velocity and projection angle of the ball were calculated using the Pythagorean equation and the trigonometric tangent function. The rate of ball spin was obtained by observing the rotation of black lines that were drawn on the ball. The angular displacement of the lines over the first ten frames after release was measured to the nearest 10º.

The uncertainties in the measured values of projection velocity and projection angle arose mainly from the uncertainties in the fit to the coordinate data for the flight of the ball. The uncertainties (95% confidence interval) were about 0.14 m/s for projection velocity and 0.6º for projection angle. The greatest source of uncertainty in the projection height arose from the sampling frequency of the video camera, and this uncertainty was taken as one half of the difference between the value at the instant of release and the value at one frame before the instant of release (about 0.07 m). The uncertainty in the ball spin rate was about 0.1 rev/s.

To address the first aim of the study we checked for systematic changes in the participant's projection variables with increasing ball spin rate. The projection velocity, angle, and height were plotted against spin rate, and a selection of curves was fitted to the data. We tested a straight line, a second-order polynomial, and a third-order polynomial. The most appropriate curve was decided by examining the distribution of the residuals and with calculations of the corrected Akaike's Information Criterion [5]. To address the second and third aims of the study the participant's effective throw distance was plotted against spin rate and a selection of curves was fitted to the data. The peak in the most appropriate curve was taken as the participant's optimum spin rate.

As mentioned previously, projection velocity, projection angle, and projection height are inter-related [1,6]. In a soccer throw-in the projection velocity decreases with increasing projection angle because of the musculoskeletal structure of the human body is such that a player can exert more force on the ball when throwing horizontally than when throwing vertically. The relationship between projection velocity (v) and projection angle (θ) is given by

$$v = \sqrt{\frac{2\left(F_o - a\theta\right) l}{m}} \,, \tag{1}$$

where F_o is the average force exerted on the ball for a horizontal release angle, l is the acceleration path length of the ball (about 1.3 m), m is the mass of the ball (0.43 kg), and a is a constant that characterizes the force decrease with increasing release angle [1]. In a soccer throw-in the projection height increases with increasing projection angle because the arm angle at the instant of release increases. The relationship between projection height (h) and projection angle (θ) is given by

$$h = h_{shoulder} + l_{arm} \sin\left(A\theta + \alpha_o\right), \tag{2}$$

where $h_{shoulder}$ is the height of the player's shoulders when standing upright (1.5 m), l_{arm} is the length of the player's outstretched arms (0.8 m), A is the rate of increase in the arm angle with increasing release angle, and α_o is the arm angle for a horizontal release [1]. In a soccer throw-in the strong relationship between projection velocity and projection angle (equation 1) is the main reason why the optimum projection angle for achieving maximum distance is about 30º rather than 45º. Knowledge of a player's relationships between projection velocity, angle, and height (equations 1 and 2) are necessary for an accurate mathematical model of the soccer throw-in. To quantify these relationships, the participant's projection velocity and projection height were plotted against projection angle and equations 1 and 2 were fitted to the data.

2.3. Mathematical model

To address the fourth aim of the study we performed simulations using a mathematical model of the throw-in. The trajectory of the soccer ball was analyzed in a rectangular coordinate system where the positive x-axis is in the forward horizontal direction and the positive y-axis is vertically upwards. The aerodynamic flight trajectory equations of the soccer ball are then

$$\frac{d^2x}{dt^2} = -kv\left(C_D \frac{dx}{dt} + C_L \frac{dy}{dt}\right)$$

$$\frac{d^2y}{dt^2} = kv\left(C_L \frac{dx}{dt} - C_D \frac{dy}{dt}\right) - g \,,$$

where $v = \sqrt{[(dx/dt)^2 + (dy/dt)^2]}$ is the velocity of the ball relative to the air, C_D is the drag coefficient, C_L is the lift coefficient, and g is the acceleration due to gravity (9.81 m/s^2) [1,7]. The constant k is given by $k = \rho S/(2m)$, where ρ is the air density (1.225 kg/m^3 at sea level and 15ºC), S is the cross-sectional area of the ball (0.038 m^2), and m is the mass of the ball (0.43 kg). The lift coefficient of a soccer ball increases exponentially with increasing spin parameter, from $C_L = 0$ for no spin, up to a limiting value of about $C_L = 0.35$ [8,9,10]:

$$C_L = -0.35\,e^{-7\,Sp} + 0.35\,.$$

The spin parameter is the ratio of the ball's tangential speed at its equator to its center of mass speed, and is given by $Sp = r\omega/v$ where r is the radius of the ball and ω is the ball spin rate (in radians per second). For a spinning soccer ball the drag coefficient increases slightly with increasing spin parameter;

$$C_D = C_{Do} + 0.5\,Sp\,,$$

where C_{Do} is the drag coefficient at zero spin [8]. At velocities typical of the soccer throw-in (10–20 m/s), a soccer ball that is projected with zero spin has a drag coefficient of about C_{Do} = 0.25 [10,11].

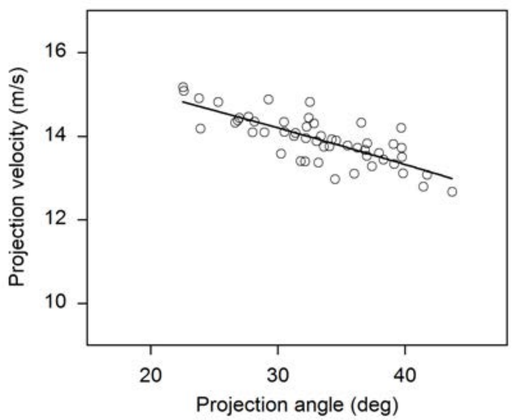
If the initial conditions of the ball (i.e., projection velocity, projection angle, projection height, and spin rate) are known, the trajectory of the ball may be computed and the distance of the throw determined. Because the projection variables are inter-related, we used the participant's measured relationships for $v(\theta)$, $h(\theta)$, and $v(\omega)$ to generate the initial conditions for the flight trajectory equations. The flight trajectory equations are non-linear and so the flight trajectories were computed using numerical methods implemented in a technical computing software package (Mathematica; Wolfram Research, Champaign, IL, USA). The throw distances obtained with the mathematical model were then compared to the experimental data for the effect of ball spin rate on throw distance.

3. Results and Discussion

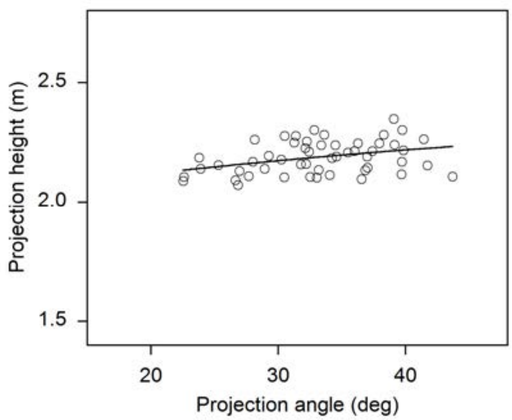
The mean values for the participant's five preferred throws were: distance, 18.7 ± 1.5 m (mean ± SD); projection velocity, 14.4 ± 0.6 m/s; projection angle, 31.8 ± 7.2°; projection height, 2.17 ± 0.05 m; and ball backspin rate, 1.2 ± 0.3 rev/s. These values are similar to those reported for skilled male players in other studies of the soccer throw-in [12,13,14].

As expected, the projection velocity decreased with increasing projection angle and the projection height increased slightly with increasing projection angle (Figure 2). The model fit parameter values were F_o = 45 ± 3 N (±95% CI) and a = 0.40 ± 0.09 N/deg for projection velocity, and A = 0.7 ± 0.5 and α_o = 37 ± 16° for projection height. These values are similar to those for the skilled male player examined by Linthorne and Everett [1].

Across the range of backspin rates used in this study (0–2.7 rev/s), the participant's projection velocity remained almost constant (13.9 ± 0.6 m/s; mean ± *SD*) and no systematic trend with increasing spin rate was evident (Figure 3a). That is, the action of applying backspin to the ball did not reduce the participant's ability to produce a high projection velocity. Similarly, across the range of backspin rates used in this study the participant's projection angle and projection height remained almost constant (33.1 ± 5.2° and 2.19 ± 0.07 m, respectively). For all three variables a straight line was the best fit to the data. The gradient of the projection velocity fit was zero (0.14 ± 0.26 m/s per rev/s; ±95% CI), as was the gradient of the projection angle fit (–0.8 ± 2.4 deg per rev/s) and the gradient of the projection height fit (–0.018 ± 0.030 m per rev/s). These results indicate that changes in throw distance were due to systematic changes in ball spin rate and were not due to systematic changes in projection velocity, projection angle, or projection height. For the throw distance plot a straight line was also the best fit to the data (Figure 3b). Throw distance tended to increase as more backspin was applied to the ball, at a rate of 0.62 ± 0.48 m per 1 rev/s increase in backspin. There was no clear optimum backspin rate that produced the greatest throw distance.



a



b

Fig. 2. These plots show the effect of projection angle on (a) projection velocity and (b) projection height. The solid lines are regression fits for equations 1 and 2, respectively. The relationship between projection velocity and projection angle has a very strong influence on the participant's optimum projection angle.

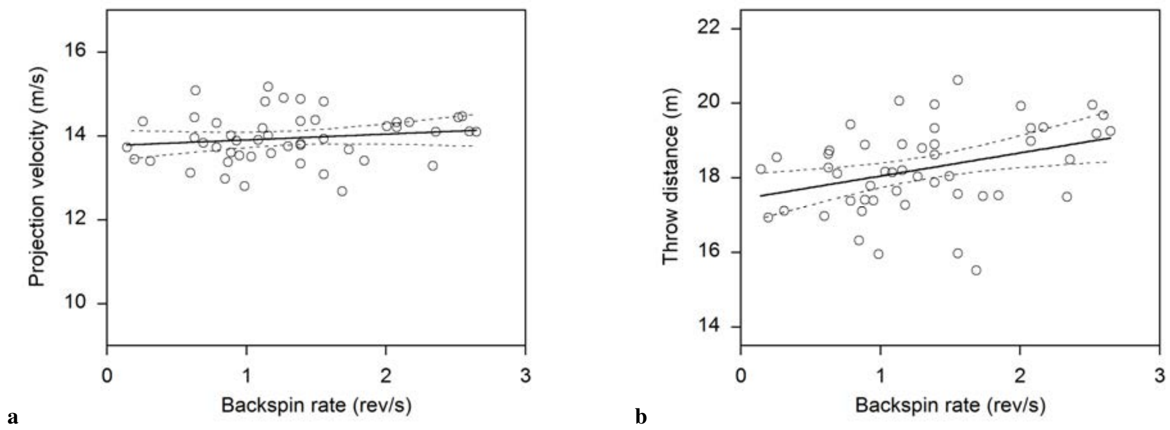


Fig. 3. These plots show the effect of ball backspin rate on (a) projection velocity and (b) throw distance. The solid lines are linear regression fits and the dashed lines show the 95% confidence interval of the regression lines. The process of applying backspin to the ball did not reduce the participant's ability to produce a high projection velocity, and changes in throw distance were not due to systematic changes in the projection angle or projection height. Throw distance tended to increase as more backspin was applied to the ball.

The mathematical model indicates there should be an inverted-u relationship between throw distance and backspin rate, with a maximum throw distance at a backspin rate of about 3 rev/s (Figure 4a). (For spin rates above 3 rev/s the gain in distance due to the greater lift is outweighed by the loss in distance due to the greater drag.) The mathematical model also indicates the optimum projection angle should steadily decrease with increasing backspin, from about 31° for no spin to about 24° at 5 rev/s. The predictions of the mathematical model are consistent with the experimental data. Although the mathematical model predicts an inverted-u relationship, the variability in our experimental data and the limited range of backspins used by the participant (0–2.7 rev/s) did not allow us to resolve this relationship. We expect few players to be able to produce a backspin rate greater than about 3 rev/s. Therefore, to achieve the greatest possible throw distance we recommend that players release the ball with the greatest possible backspin.

The experimental part of this study examined performances by only one male participant. A player's ability to produce a long throw is mainly determined by their muscular strength [15]. To help generalize the results of the study we used the mathematical model to investigate the effects of muscular strength on throw-in performance. The force exerted by the player on the ball (F_o in equation 1) was varied over a wide range. Our calculations show that stronger players are able to throw the ball substantially farther (Figure 4b), but the optimum backspin rate remains at about 3 rev/s.

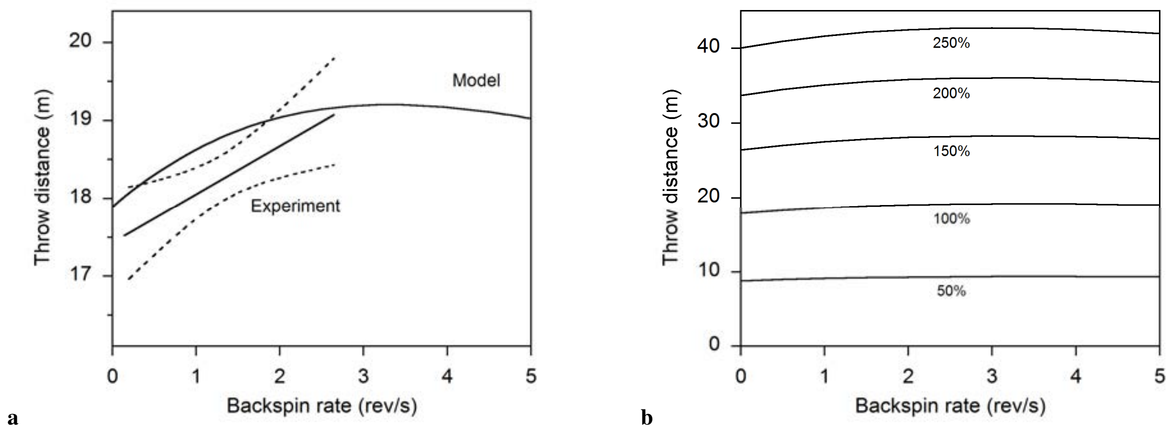


Fig. 4. Plot (a) shows the relationship between throw distance and ball backspin rate predicted by the mathematical model (when using parameter values for the participant in this study). The optimum backspin rate that maximizes throw distance is about 3 rev/s, which is about the maximum achievable for many players. The predictions of the mathematical model are consistent with the experimental data from the participant (regression line and 95% CI from Figure 3b). Plot (b) shows the calculated effect of muscular strength (as a percentage of the strength of the participant in this study). Stronger players are able to throw the ball farther, but the optimum backspin rate remains at about 3 rev/s.

4. Conclusion

We recommend players apply the highest possible rate of backspin when performing a long soccer throw-in. Even though the increase in flight distance achieved with a high backspin is relatively modest (about 7%), it could increase the team's goal-scoring opportunities. An accurate mathematical model of the effect of backspin on the distance achieved in a soccer throw-in must include the interactions between the ball, the player, and the throwing movement. The process of applying backspin to the ball did not reduce the participant's ability to produce a high projection velocity. However, the decrease in projection velocity with increasing projection angle had a very strong influence on the participant's optimum projection angle, reducing his optimum angle from 45º to about 30º.

References

[1] Linthorne NP, Everett DA. Release angle for attaining maximum distance in the soccer throw-in. *Sport Biomech* 2006;5:243–60.
[2] Stefanyshyn DJ, Wannop JW. Biomechanics research and sport equipment development. *Sport Eng* 2015;18:191–202.
[3] Knudson D, Bahamonde R. Effect of endpoint conditions on position and velocity near impact in tennis. *J Sport Sci* 2001:19:839–44.
[4] Nunome H, Ikegami Y, Kozakai R, Apriantono T, Sano S. Segmental dynamics of soccer instep kicking with the preferred and non-preferred leg. *J Sport Sci* 2006;24:529–41.
[5] Motulsky H, Christopoulos A. *Fitting models to biological data using linear and nonlinear regression*. Oxford: Oxford University Press; 2002.
[6] Red WE, Zogaib AJ. Javelin dynamics including body interaction. *J Appl Mech* 1977;44:496–8.
[7] Bray K, Kerwin DG. Modelling the long soccer throw-in using aerodynamic lift and drag. In: Hubbard M, Mehta RD, Pallis JM, editors. *The engineering of sport 5 (Vol. 1)*. Sheffield: International Sports Engineering Association; 2004. p. 56–62.
[8] Asai T, Seo K, Kobayashi O, Sakashita R. (2007). Fundamental aerodynamics of the soccer ball. *Sport Eng* 2007;10:101–10.
[9] Carré MJ, Goodwill SR, Haake SJ. Understanding the effect of seams on the aerodynamics of spinning and stationary footballs. *Proc IMechE, Part C: J Mech Eng Sci* 2005;219:657–66.
[10] Goff JE, Carré MJ. Soccer call lift coefficients via trajectory analysis. *Eur J Phys* 2010;31:777–84.
[11] Alam F, Chowdhury H, Moria H, Fuss FK. A comparative study of football aerodynamics. *Procedia Eng* 2010;2:2443–8.
[12] Kerwin DG, Bray K. Quantifying the trajectory of the long soccer throw-in. In: Hubbard M, Mehta RD, Pallis JM, editors. *The engineering of sport 5 (Vol. 1)*. Sheffield: International Sports Engineering Association; 2004. p. 63–9.
[13] Kollath E, Schwirtz A. Biomechanical analysis of the soccer throw-in. In: Reilly T, Lees A, Davids K, Murphy WJ, editors, *Science and football*. New York: E & FN Spon; 1988. p. 460–7.
[14] Messier SP, Brody MA. Mechanics of translation and rotation during conventional and handspring soccer throw-ins. *Int J Sport Biomech* 1986;2:301–15.
[15] de Carnys GMS, Lees A. The effects of strength training and practice on soccer throw-in performance. In: Reilly T, Korkusuz F, editors. *Science and football VI*. Abingdon: Routledge; 2009. p. 302–6.